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Interoperable Localization for Mobile Group Users

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Abstract

This paper studies the problem of real-time wireless localization for mobile group users, which can be used in many applications such as fire rescue and safety management in construction sites. However, due to the mobility of users and the instability of wireless signals, we find that traditional localization methods do not perform well, and the localization accuracy is thus not acceptable. To solve this problem, we propose to localize mobile users by exploiting their interrelated information. The mutual distance information among the users are exploited to get better localization performance for all the users. We first theoretically prove that the proposed scheme can improve the localization probability and accuracy. Furthermore, an Interoperable Localization Method (ILM) is designed, which extends the Kalman filter to alleviate the influence of noisy and unstable wireless signals. Finally, extensive experimental results demonstrate that our method outperforms the fixed anchor-based methods by 20%–45% in terms of localization accuracy and 20%–50% in terms of localization probability.

Keywords: Localization for mobile group users, wireless localization, interoperable localization, mobile localization, Kalman filter

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1. Introduction

In recent years, wireless localization has attracted considerable research interest because of the increasing demand for location-based services in the military, industry and Wireless Sensor Networks (WSNs) [1, 2]. Among them, localization for mobile objects is one of the most significant applications [3]. For example, indoor localization, which attempts to find the accurate positions of person and object inside a building, mall, ..., etc [4], can provide the position information to provide services in various categories including the location detection of firefighters in a building on fire, location detection of products stored in a warehouse, location detection of medical personnel or equipment in a hospital, and finding tagged maintenance tools and equipment scattered all over a plant, tracking, monitoring, healthcare, billing and so on [5, 6, 7]. For example, if we can know the exact position of the firefighters, we can get more information about the fire, monitor the security situation of firefighters and direct rescue operations. Another example is that, the high-risk construction industry in Hong Kong accounts for nearly 1/5 of all industrial accidents. This accident occurrence rate could be greatly reduced if safety management systems could continuously monitor the real-time locations of mobile workers and automatically issue warnings when these workers are close to some hazardous areas. However, because of the mobility and sheltered by barrier, the signal from fixed anchors may not well received.

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The Global Positioning System (GPS) is one of the most well-known and widely used localization techniques [8]. However, two factors limit its application for mobile group users indoor. First, the localization error, which is approximately 10 meters, is too large to satisfy the demand of location-based services. Second, it performs poorly in indoor environments such as mines, markets, airports and warehouses. Fortunately, we have another type of localization technology: localization with wireless signals, e.g., Time of Arrival (TOA) [9], Time Difference of Arrival (TDOA) [10], Angle of Arrival (AOA) [11] and Received Signal Strength Indication (RSSI) [12]. These approaches require a set of specialty nodes known as anchors, which know their own location either through manual configuration or through a GPS receiver [13]. These technologies work well for the localization of static users. However, due to various reasons, such as the mobility of users, the instability of the wireless signal [14], multipath propagation and Non-Line of Sight paths (NLOS) [15], these localization techniques do not perform well for mobile users. Moreover, the solutions provided by these localization algorithms are acceptable only when there is sufficient distance information from the anchors. However, in certain scenarios, due to sparse anchor deployment, short radio communication ranges, and physical obstacles, a sufficient number of accurate measurements may not be available. In such cases, the localization accuracy declines sharply [16, 17]. Hence, developing a reliable algorithm to address these localization problems is important and requires more study.

Mobility-aided localization methods, in which mobile anchors are exploited to aid in localization, have been investigated recently in studies such as [18] and [19]. A mobile anchor can follow mobile users in mobility-aided localization methods, which can improve the localization performance. However, it is well known that a moving anchor can cover only a small area within a reasonable time [20]. Obviously, adding more mobile anchors in the network area leads to better performance, but this incurs high costs. Moreover, the movement of the anchor increases energy consumption and introduces greater hardware support requirements, such as mobile devices. Therefore, mobility-aided methods still cannot solve the localization problem for mobile group users, which may include many users.

Another research interest is cooperative localization, in which the information among the users are exploited to help the localization [21, 22, 23]. The most common idea is that some users are localized first and then they can be exploited as virtual anchors to localize others who cannot. Thus there is a delay of the positioning for the users, which also influences the localization accuracy. Another problem is that, they focus on localizing the users who are immobile. If the users are mobile, due to the users' mobilities and signal noise, the localization accuracy is limited. For example, in [24], the localization accuracy achieved in the static network seems feasible, but failed in the dynamic networks. Patwari N et al present cooperative measurement-based statistical models and give the localization error analytically in [25]. They propose a distributed localization algorithm by successive refinement, which still cannot avoid the delay problem. In [26], the authors propose convex SDP (semidefinite programming) estimators specifically for the RSS-based localization in both noncooperative and cooperative shcemes, and the maximum likelihood estimator is appended to the convex estimator. However, the localization error is more than 1.5 meter in most cases, which is too large.

This paper presents a novel approach for localizing mobile group users. In the proposed approach, the mobile users not only communicate with several fixed anchors but also with other mobile users. Then, the distances among them can be calculated. Based on these information, the mobile users can help themselves (as a whole) to get better localization performance. This localization idea is designed and combined with the extension of KF, which further improves the localization performance. The main contributions of this paper are listed as follows:

1. To localize mobile group users, we introduce the idea of interoperable localization, in which mobile users serve as "mobile anchors" to help locate each other.
2. A series of theoretical analyses regarding why the localization performance can be improved are presented.
3. We extend the Kalman filter algorithm to alleviate the influence of the noise in the environment and the unstable of wireless signals.
4. We conduct extensive experiments to compare the proposed solution with traditional solutions, and the effectiveness is validated by the experimental results.

The remainder of this paper is organized as follows. Section 2 reviews related work. The experimental results of the traditional fixed anchors-based localization method is presented in Section 3. The details of the proposed localization scheme are elaborated upon in Section 4. Section 5 demonstrates the experimental results. We conclude the paper in Section 6.

2. Related Work

With the continuing development of wireless communication and mobile computing technologies, applications based on wireless localization are becoming increasingly common. The localization problem has receivec tremendous attention from the research community because the localization performance is an absolute necessity for correct operation of the systems [20]. The existing localization schemes proposed are broadly categorized into five groups: distributed algorithm, centralized algorithm, iterative algorithm, mobility-assisted approach and statistical approach according to [27] and are divided into "sparse vs. dense", "anchor based vs. anchor free", "indoor vs. outdoor", "cooperative vs. non-cooperative" and "static vs. mobile" according to [28]. According to whether the distance information between anchors and users is required, wireless localization methods can be broadly divided into two categories: range-based localization and range-free localization [29, 30, 31]. While according to wheather the users can cooperative with each other, wireless localization methods can be divided into cooperative localization and non-cooperative localization [32]. In this paper, we focus on range-based cooperative localization methods. The major studies related are summarized into three groups and the details are illustrated as follows.

2.1. Range-Based Localization Scheme

Normally, the range-based localization approach utilizes the ranging information between the user and anchors whose locations are already known. For example, in [33], the authors consider a problem of TOA-based localization for a passive object. They propose linearizing the system model by introducing a range variable first and then solve the linearized localization problem via the Tikhonov regularization method. However, the ranging information is always contaminated by the environment or uncertainty, which affects the performance of the localization method. To solve this problem, some studies propose combining two or more of the methods to improve the localization accuracy and reduce the energy consumption [34]. For example, a hybrid TOA and RSS linear least squares localization method is derived in [35]. However, these combined methods increase the algorithm complexity. Moreover, if the anchors are sparsely deployed, the deployment of the anchors is extremely irregular, or there are too many obstacles in the environment, the real-time positions of the users still cannot be achieved. Consequently, these methods have special requirements for anchor quantity and distribution.

2.2. Mobile Anchor-Based Localization Scheme

or mobility-assisted approach In addition to the use of stationary anchors, several other studies introduce mobile anchors to help with the localization process [36, 37]. In [38], a single mobile anchor is introduced to enable the sensor nodes to construct two chords of a communication circle, and the intersection of the perpendicular bisectors of these two chords is then calculated to pinpoint the sensors positions. However, it introduces only one mobile anchor due to the hardware costs and this anchor moves randomly through the sensing field. Thus, it is possible that some of the sensor nodes cannot be localized. To solve this problem, a path planning-based scheme is proposed in [39] that not only improves the localization accuracy but also maximizes the number of sensor nodes that can be localized. However, the single moving anchor covers just a small area within a reasonable period of time and thus cannot achieve the real-time localization of many users. Although adding more mobile anchors leads to better performance, more expensive device hardware is required.

2.3. Cooperative Localization Schemes

Another research interest is localizing the users cooperatively, i.e., the mobile users cooperate with each other to improve the localization accuracy [40, 41]. In [42], a backbone, i.e., a subset of nodes that are intermediaries between multiple beacon nodes, is constructed, which guides the localization of other nodes. Each node estimates its location using its neighbors locations from the previous iteration. Moreover, for better localization of the non-backbone nodes and avoidance of the rigidity problem, 2-hop neighboring distances are approximated. In [43], the authors propose a cooperative approach in which a node whose position has been estimated will be added to the reference node database to localize other unknown nodes. The reference nodes locate their one-hop neighbors first, and then newly added references further locate other one-hop neighbors. However, this process propagates and accumulates the error in the network. In [44], a decentralized cooperative method called *PulseCounting* is proposed. It forms an estimation of the current location by accumulating the segments of the users walking steps, and it improves the estimation accuracy by exploiting the encounters of mobile nodes. However, it must use the accelerometer and electronic compass to obtain the users walking steps and the orientation of each step, which may limit its application. It can be observed that the aforementioned methods still have problems of poor localization performance, high time complexity, etc.

In this paper, we propose localizing mobile group users using their own information and extending the Kalman filter to alleviate the effects of environmental noise and wireless signal instability.

3. Experimental Test of the Localization Method Based Solely on Fixed Anchors

In this section, we first introduce the traditional wireless localization method based solely on fixed anchors and then demonstrate its experimental results for localizing mobile users.

3.1. Fixed Anchors-Based Localization

Suppose there are m stationary anchors located at points $Q = [(x_1, y_1), (x_2, y_2), \ldots, (x_m, y_m)]$ and n mobile users with positions $P = [(X_1, Y_1), (X_2, Y_2), \ldots, (X_n, Y_n)]$. In fixed anchors-based localization, the signal propagation distance r_{ij} between user i and anchor j can be measured by $r_{ij} = (t_j - t_i) \times v$, where t_j is the time at which the signal is sent from anchor j, t_i is the time at which the signal is received by user i, and v is the velocity of signal transmission. Then, the location of user i, denoted by (X_i, Y_i), can be estimated using nonlinear equation:

$$r_{ij}^2 = (x_j - X_i)^2 + (y_j - Y_i)^2. \qquad (1)$$

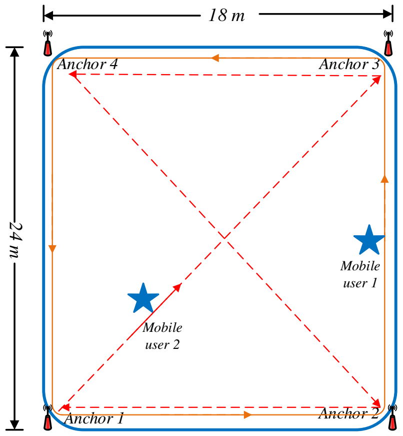


Figure 1: The experimental scenario

This represents a circle in a $2 - D$ plane, whose center is (x_j, y_j), which is the location of anchor j. The circle represents a set of possible locations for user i. It can be uniquely localized when three or more signal circles have a common intersetion point (X_i, Y_i) [45].

3.2. Experimental Result

We conducted the simulation experiment on an 18×24 m^2 rectangular area to test the localization performance of the method based on fixed anchors. Six nodes were used in our experiment. Four of them were used as anchors located at the four corners of the experimental area. The other two acted as mobile users, and one of them moves along the rectangular edges of the area and the other moves along both the diagonals and the edges of the square. Fig. 1 illustrates the experimental environment. The mobile users received signals from the four anchors each second to calculate the distances between them. Then, we used the aforementioned method to localize the users.

As shown in Figs. 2 and 3, the trace of mobile users often deviate seriously from the users true course. The maximum localization errors between the real value and the estimated value are 3.6191 m and 3.0889 m, and the average localization errors are 1.4221 m and 1.3563 m, respectively. This result motivates us to design a new method to improve the localization accuracy. The basic idea is presented in the next section.

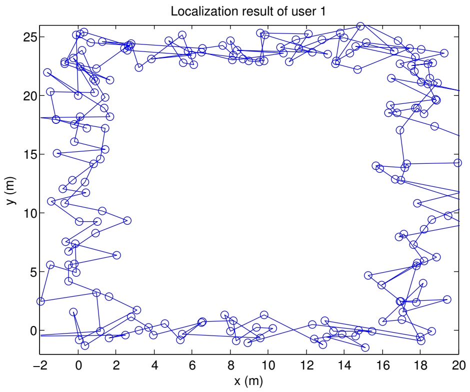


Figure 2: Localization result of user 1

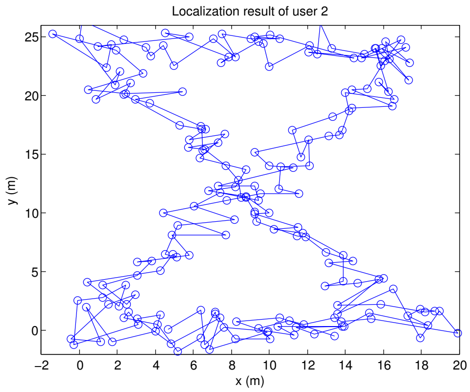


Figure 3: Localization result of user 2

4. The Interoperable Localization Method

This section presents our proposed interoperable localization method based on “mobile anchors.” Different from other localization methods, the users in our proposed method can communicate with others and act as “mobile anchors” for each other, which can increase the reference information for localization.

4.1. The Basic Idea of Interoperable Localization

This section describes the basic idea of the proposed interoperable localization method. Fig. 4 gives a simple example in which A_i ($i = 1, 2, 3, 4$) are the fixed anchors and U_i ($i = 1, 2, 3$) are the non-localized mobile users. As shown in the figure, U_2 can receive signals from more than three anchors (A_1, A_2, A_3 and A_4). Obviously, its position can be estimated using a traditional fixed anchors-based localization method. However, some users may not be able to successfully receive signals from enough anchors. For example, U_1 and U_3 may only receive signals from $\{A_1, A_2\}$ and $\{A_3, A_4\}$, respectively. Therefore, they cannot be localized based on the traditional localization method. However, they can both receive signals from U_2, whose position has been estimated already, which motivates us to use U_2 as a “mobile anchor” to help U_1 and U_3 for localization.

The basic idea is that the mobile users communicate with each other and calculate the distances among them. Then, the users whose locations have already been localized can be exploited to localize the users whose locations have not. For one thing, the introduction of “mobile anchors” can help to improve the localization probability. For another, this method is also expected to improve the localization accuracy, which will be discussed in the following section.

4.2. Performance Analysis of the Proposed Localization Method

In this section, we provide analyses to prove the effectiveness of the proposed localization method. Here, we consider the scenario in which there are three non-collinear anchors (A_1, A_2, and A_3) and three users (U_1, U_2 and U_3). We say U_i can hear A_j if U_i can receive the anchor information from A_j. Assume that the distance from U_i to A_j is d_i, the distance from U_i to $A_{(j+1)}$ is d_i', the distance between U_i and U_j is d_{ij}, and the distance from A_i to A_j is $d_{A_iA_j}$. For ease illustration, the analyses are based on 12 scenarios. Note that, based on this, the analyses can be easily extended to scenarios with more anchors and users. Table 1 shows a summary of the results and the details are presented as follows (owing to space constraints, some of them are shown in the appendix).

Theorem 1. *If each of the users can receive the signal of one and only one anchor (case 7 in Table 1), then the users can be localized.*

Proof. Assume U_1 can hear A_1, U_2 can hear A_2, and U_3 can hear A_3, Then,

1. If $d_{A_1A_2} = d_{12} + d_1 + d_2$ or $d_{A_1A_2} = d_{12} - d_1 - d_2$, namely, U_1 and U_2 are on line A_1A_2, then U_1 and U_2

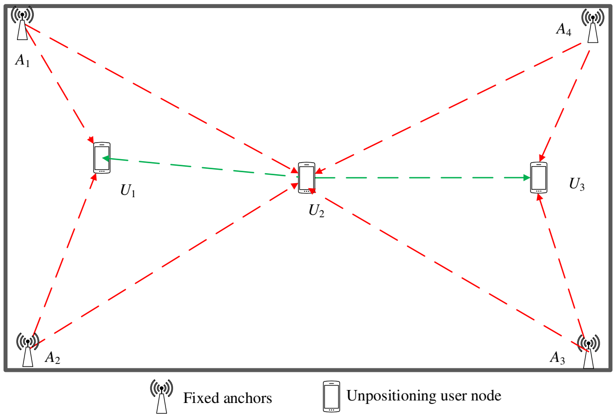


Figure 4: A simple illustration of mobile localization (U_1 and U_3 cannot be localized based on the traditional method with fixed anchors)

Table 1: Summaties of the analyses

		A_1	A_2	A_3	Result			A_1	A_2	A_3	Result
1	U_1	★	★	★	×	7	U_1	★	✰	✰	√
	U_2	✰	✰	✰			U_2	✰	★	✰	
	U_3	✰	✰	✰			U_3	✰	✰	★	
2	U_1	★	★	✰	×	8	U_1	★	★	✰	√
	U_2	✰	✰	★			U_2	★	✰	✰	
	U_3	✰	✰	✰			U_3	✰	✰	★	
3	U_1	★	★	✰	×	9	U_1	★	★	✰	√
	U_2	✰	✰	★			U_2	★	★	✰	
	U_3	✰	✰	★			U_3	✰	✰	★	
4	U_1	★	★	★	×	10	U_1	★	★	★	√
	U_2	★	★	★			U_2	★	★	✰	
	U_3	✰	✰	✰			U_3	✰	★	★	
5	U_1	★	★	★	×	11	U_1	★	★	★	√
	U_2	★	★	✰			U_2	★	★	★	
	U_3	✰	✰	✰			U_3	✰	★	✰	
6	U_1	★	★	★	×	12	U_1	★	★	★	√
	U_2	★	✰	✰			U_2	★	★	★	
	U_3	★	✰	✰			U_3	★	★	★	

★: U_i can hear A_j; ✰: U_i cannot hear A_j; √: the users can be localized; ×: the users cannot be localized.

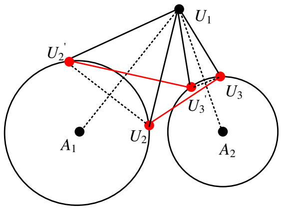


Figure 5: The scenario when U_2 and U_3 can hear different anchors

can be positioned. U_3 can also be localized as it can hear U_1, U_2 and A_3. In all, the users can be localized in this situation.

2. If one of U_1 and U_2 is on line A_1A_2, suppose U_1 here, then U_1 can be positioned. U_2 and U_3 can hear $\{U_1, A_2\}$ and $\{U_1, A_3\}$ respectively. Draw two circles with center U_1 and radiuses d_{12} and d_{13}, and then their intersections with circles A_2 and A_3 are $\{U_2, U_2'\}$ and $\{U_3, U_3'\}$ respectively. U_2 and U_3 can be positioned for $U_2U_3 \neq U_2'U_3'$, as shown in Fig. 5. Therefore, the users can be localized in this situation.
3. If both U_1 and U_2 are not on line A_1A_2, assume that U_1 can be positioned; then, U_2 and U_3 can also be positioned. While U_1 rotates on circle A_1, with center A_1 and radius d_1, it is hard to find another group of U_2 and U_3 that can satisfy the conditions. Therefore, the users can be localized in this situation.

□

Theorem 2. *If one of the users can receive the signal of two anchors, the second user can receive the signal of one of the two anchors and the third user can receive the signal of the third anchor (case 8 in Table 1), and then the users can be localized.*

Proof. Assume that U_1 can hear A_1 and A_2, U_2 can hear A_2, and U_3 can hear A_3. Then,

1. If $d_{A_1A_2} = d_1 + d_2$, i.e., U_1 is on line A_1A_2, then it can be localized. U_2 and U_3 can hear $\{U_1, A_1\}$ and $\{U_1, A_2\}$, respectively. Start from U_1 as the center, and then the circles with radiuses d_{12} and d_{13} respectively intersect with circles A_1 and A_2 at points $\{U_2, U_2'\}$ and $\{U_3, U_3'\}$ respectively. U_2 and U_3 can be localized for $U_2U_3 \neq U_2'U_3'$, as shown in Fig. 5. Therefore, the users can be positioned in this situation.
2. If $d_{A_1A_2} < d_1 + d_2$, i.e., U_1 is not on line A_1A_2, then two possible localizations of U_1 that are symmetric with respect to line A_1A_2 can be obtained. For certain U_1, U_2 and U_3 can be localized according to the analysis in (1) because they can hear $\{U_1, A_1\}$ and $\{U_1, A_2\}$, respectively. Therefore, the users can be positioned in this situation.

□

Theorem 3. *If two of the users can receive the signals of two anchors and the last user can receive the signal of the third anchor (case 9 in Table 1), then the users can be localized.*

Proof. Assume that U_1 and U_2 can hear A_1 and A_2 and that U_3 can hear A_3. From the analysis in Theorem 3, we know that the users can also be localized in this situation. This is because the only difference between the situations in case 9 and case 8 is that U_2 can hear more anchors. □

Theorem 4. *If one of the users can receive the signals of all three anchors and one of the anchors that the other two users can receive the signal of is different (case 10 in Table 1), then the users can be localized.*

Proof. Assume that U_1 can hear all three anchors and that U_2 and U_3 can hear one or two different anchors. U_1 can be localized because it can hear three non-collinear anchors. For U_2 and U_3,

1. If U_2 and U_3 can each hear one and only one anchor, we suppose that U_2 can hear A_1 and that U_3 can hear A_2. They can be positioned according to the analysis in Theorem 2. Therefore, the users can be localized in this situation.
2. If one of them can hear one and only one anchor and the other can hear two anchors, we suppose that U_2 can hear A_1 and that U_3 can hear A_2 and A_3 here. U_3 can be localized as it can hear U_1, A_2 and A_3. U_2 can also be positioned because it can hear U_1, A_1 and U_3. Thus, the users can be localized in this situation.
3. If all of them can hear two anchors, suppose that U_2 can hear A_1 and A_2 and that U_3 can hear A_2 and A_3. U_2 can be positioned because it can hear U_1, A_1 and A_2. U_3 can also be localized because it can hear U_1,

A_2 and A_3. Therefore, the users can be localized in this situation.

□

Theorem 5. *If two of the users can receive the signals of all three anchors and the third user can receive the signal of one and only one anchor (case 11 in Table 1), then the users can be localized.*

Proof. Assume that U_1 and U_2 can hear all three anchors and that U_3 can hear A_2. U_1 and U_2 can be positioned as they can hear three non-collinear anchors. U_3 can also be localized as it can hear U_1, U_2 and A_2. In total, the users can be localized in this situation. □

As observed from the theorems above, the users who cannot be localized by the traditional methods, in which the users must receive the signals of more than three anchors, can be localized according to the proposed localization method. Thus the proposed method can improve the localization performance.

4.3. The Detailed Interoperable Localization Method Based on EKF

This section presents the interoperable localization method by extending the Kalman filter.

The innovation of our proposed algorithm is that we utilize the information from not only the fixed anchors but also the users themselves. Moreover, we extend the Kalman filter to alleviate the effects of noisy environments and wireless signal instability. First, we introduce the motion model for the users. Second, we describe the measurement model for the distances. Finally, we introduce the proposed algorithm with "mobile anchors" by extending the Kalman filter, which is denoted as MEKF.

(1) The Motion Model

Mobile users moving through the environment are described by their localizations and velocities in the $X-Y$ plane. Thus the state of one user at time t can be described by a state vector: $x(t) = [Lx(t), Ly(t), Vx(t), Vy(t)]$, where $Lx(t)$ and $Ly(t)$ specify the $x-$ and $y-$values and $Vx(t)$ and $Vy(t)$ are the user's speed in the $x-$ and $y-$directions, respectively. Consequently, the state vector of n users in our proposed method can be described as follows:

$$X(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T, \tag{2}$$

where $x_i(t)$ represents the state of user i. A denotes the transpose operation. Therefore the motion of the users can be described by:

$$X(t/t-1) = A * X(t-1) + W(t-1), \tag{3}$$

where $W(t-1)$ represents noise in the process, which is assumed to be a white Gaussian noise sequence with a mean of zero and the covariance matrix Q. A is the state transition matrix, which maps the forward state transition from $t-1$ to t. It is defined as follows:

$$A = \begin{bmatrix} a & O & \ldots & O \\ O & a & \ldots & O \\ \vdots & \vdots & \ddots & \vdots \\ O & O & \ldots & a \end{bmatrix}, \tag{4}$$

where O is a fourth-order matrix, all of whose elements are zero, and a can be described as follows because the state vector of user i at time t can be predicted as the same as that at time $t-1$ (T is the sampling time interval between two successive measurement times):

$$a = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{5}$$

(2) The Measurement Model

The measurement equation of the users at time instant t can be described as:

$$Z(t) = f(X(t)) + V(t), \tag{6}$$

where $V(t) \sim N(0, R)$ is a white noise sequence that represents the measurement noise and $Z(t)$ is the measurement vector at time t, i.e., the vector of the vector of the distances between the anchors and the users or between any two users. We take the square of the distances to create the measurement vector. We then have the following:

$$\begin{aligned} Z(t) = [&D_{11}^2(t), \ldots, D_{ij}^2(t), \ldots, D_{mn}^2(t), \\ &D_{12}^2(t), \ldots, D_{jk}^2(t), \ldots, D_{(n-1)n}^2(t)]^T, \end{aligned} \tag{7}$$

where $D_{ij}^2(t)$ describes the square of the distance between anchor i and user j (i=1, 2, …, m; j=1, 2, …, n) and $D_{jk}^2(t)$ represents the square of the distance between user

j and user k (j, k=1, 2, …, n; and $j \neq k$), both of which can be described as follows:

$$D_{ij}^2(t) = (L_{jx}(t) - A_{ix})^2 + (L_{jy}(t) - A_{iy})^2 + V(t), \quad (8)$$

$$D_{jk}^2(t) = (L_{jx}(t) - L_{kx}(t))^2 + (L_{jy}(t) - L_{ky}(t))^2 + V(t), \quad (9)$$

where A_{ix} and A_{iy} are the $x-$ and $y-$coordinates of anchor i, respectively (i=1, 2, …, m). Here, $L_{jx}(t)$ and $L_{jy}(t)$ epresent the $x-$ and $y-$coordinates of user j at time t, respectively (j=1, 2, …, n).

(3) The Interoperable Localization Algorithm

This section describes the proposed algorithm (Algorithm 1). The extended Kalman filter operates recursively on streams of noise to produce a statistically optimal estimate of the locations of users.

In more detail, before the recursive localization process begins, the state $X\_p(0)$, the error covariance $P\_p(0)$, the predicted error Q and the measurement error R are initialized. For each recursive process, the prior state estimate of the users, $X\_p(t/t-1)$, is measured at time t-1 through the nonlinear function (Formula (3)) to measure the priori state estimate at time t. Then, the a priori estimate error covariance $P\_p(t/t-1)$ at time t is also calculated as follows:

$$P\_p(t/t-1) = A * P\_p(t-1) * A^T + Q(t-1). \quad (10)$$

The measurement innovation, or the residual Y_e, is calculated, which reflects the discrepancy between the actual measurement and the predicted matrix, and the Kalman gain $K(t)$ will also be computed as follows:

$$K(t) = P_p(t/t-1) * H * (H * P_p(t/t-1) * H^T)^{-1} \quad (11)$$

where $H(t)$ is the is the partial derivative matrix of function h:

$$H(t) = \frac{\partial h}{\partial X}|X(t/t-1). \quad (12)$$

Finally, we use Equation (13) to update the a posteriori state estimate $X\_p(t)$ at time t with the calculated Kalman gain $K(t)$ in Equation (11).

$$X\_p(t) = X\_p(t/t-1) + K(t) * Y\_e. \quad (13)$$

When the calculation is complete at time t, we update the a posteriori estimate error covariance $P\_p(t)$ to estimate the next positions of the mobile users as follows:

$$P\_p(t) = eye(length(X\_p)) * P\_p(t/t-1). \quad (14)$$

For the next time instant, the preceding processes will be conducted again to calculate the new positions.

The time complexity of EKF is $O(n)$, where n is the number of non-localized users. For our proposed MEKF algorithm, the time complexity of each localizing process is $O(1)$. It turns out that our proposed method can reduce the time complexity of the localization process.

Algorithm 1 Interoperable Localization Based on EKF

```
Input: the distances $D_{ij}$ between anchor $i$ and user $j$ ($i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$) and the distances $D_{jk}$ between the non-localized user $j$ and the non-localized user $k$ ($j,k = 1,2,\ldots,n$, and $j \neq k$);
Output: the locations of the non-localized users;
Set the state $X\_p(0)$ and the error covariance $P\_p(0)$ all initially to 0. Initialize the predicted error $Q$ and the measurement error $R$;
for the times of the localization $t$:=1 to T do
    Predict the state $X\_p(t/t-1)$ according to Formula (3) and the error covariance by $P\_p(t/t-1) = A * P\_p(t-1) * A^T + Q(t-1)$ at time $t-1$;
    Calculate the predicted matrix $h\_Xp$ according to the positions of the anchors and the predicted state;
    Calculate the residual $Y\_e = D_{ij}^2 - h\_Xp$ between the actual measurement and the predicted matrix;
    compute the Kalman Gain $K(t) = P\_p(t/t-1) * H * ((H * P\_p(t/t-1) * H^T))^{-1}$;
    Correct the predicted state estimate $X\_p(t) = X\_p(t/t-1) + K(t) * Y\_e$ and error covariance $P\_p(t) = [eye(length(X\_p))] * P\_p(t/t-1)$;
end for
```

5. Experiments

To demonstrate the performance of our proposed algorithm, extensive simulation experiments are conducted. The experiments and the results will be introduced in this section.

5.1. Simulation Experiment

We first conducted the simulation in matlab2012, and the details are as follows.

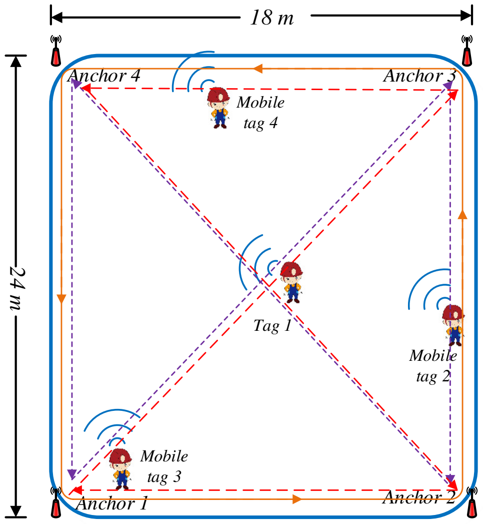


Figure 6: The experimental scenario

5.1.1. Experimental Environments

In the simulation scenario, which is 18×24 m^2, eight tags were deployed. Four of them are used as the fixed anchors, which are placed at the four corners of the region. The other four tags act as the non-localized users: the first one is located at (10 m, 12 m), the second one walks along the edges of the rectangular experimental area, and the other two walk along both the edges and the diagonals. Fig. 6 shows a snapshot of the experimental area. All of these tags communicate with each other every second to calculate the distances between them, which will be used for further calculation with the proposed algorithm. Some of the main parameters for this system are listed in Table 2. The initial state of the non-localized users is $X\_p(0) = [0, 0, 0, 0, 0, 0, \ldots, 0]^T$, which means that all of the users are located at the position (0, 0) and that their initial speed is 0 in both the x- and y-directions. In addition, Q and R are set to be $10^{-2} \times I$ and $10^3 \times I$, respectively, which are determined experimentally, and I denotes an identity matrix.

5.1.2. Experimental Results

This section presents the experimental results. To evaluate the effectiveness of our proposed algorithm, we also implemented the traditional Triangulation method (Tri) and EKF (Extended Kalman Filter) algorithm, which are based on fixed anchors, for comparison.

Table 2: Experimental Parameters

Parameters	Values
Area size (m^2)	18×24
Anchor number	4
User number	4
Communication range	20
Update frequency T(s)	1
Initial state value $X\_p(0)$	$[0, 0, 0, 0, \ldots, 0]^T$
Initial error var $P\_p(0)$	$10^6 * eye(len(X\_p(0)))$
Prediction error Q	$10^{-2} \times I$
Measurement error R	$10^3 \times I$

Figs. 7-10 show the localization results of the four users. The figures show the moving traces of the mobile users. In Fig. 7, the average localization errors achieved by Tri, EKF and MEKF are 1.1218 m, 0.6632 m and 0.5259 m, respectively, while in Fig. 8 they are 1.4868 m, 0.9230 m and 0.7534 m, respectively. In Fig. 9, they are 1.3454 m, 0.8825 m and 0.6975 m, respectively. In Fig. 10, they are 1.3409 m, 0.9778 m and 0.7970 m, respectively. Consequently, compared with the Tri method, MEKF can improve the localization accuracy by approximately 53.1%, 49.3%, 48.2% and 40.6% respectively, while compared with EKF, it improves the accuracy by 20.7%, 18.4%, 21.0% and 18.5%, respectively. The basic reason is that the introduced mobile users can act as "mobile anchors," which increases the number of available anchors.

For more detail, Fig. 11 presents the average localization errors of these four users as achieved by the three algorithms. From these average localization errors, we can verify that the localization accuracies of all the users are improved. This is because additional reference information can be got according to our proposed method, and which can alleviate the influence of noise and signal instability. Therefore, the proposed method can yield more accurate localization results.

Figs. 12 and 13 describe the max localization errors and their variance, respectively. As Fig. 12 shows, the max localization errors achieved by MEKF are lower than those of Tri by 30.6%, 39.3%, 41.3% and 32.8% for users 1-4, respectively, and lower than those of EKF by

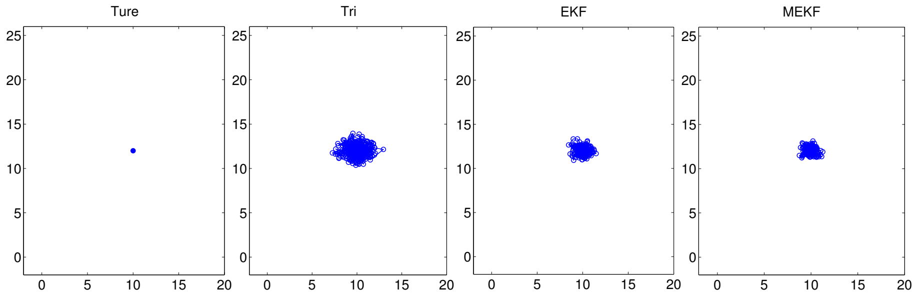


Figure 7: The localization results for user 1

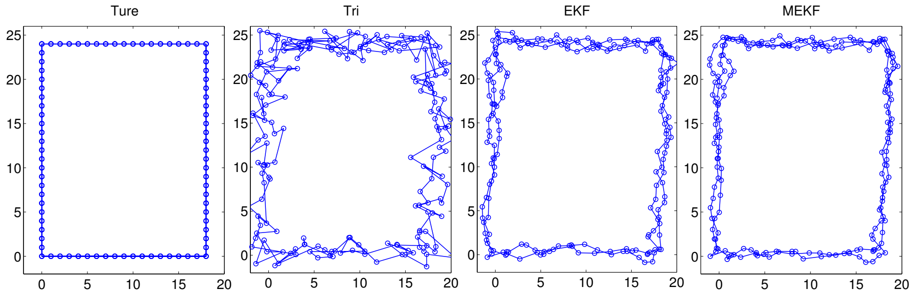


Figure 8: The localization results for user 2

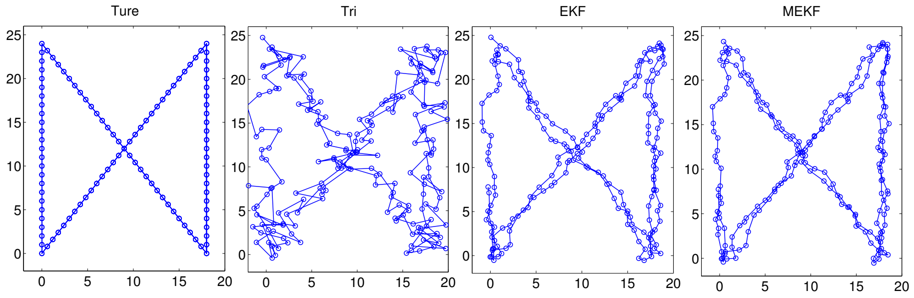


Figure 9: The localization results for user 3

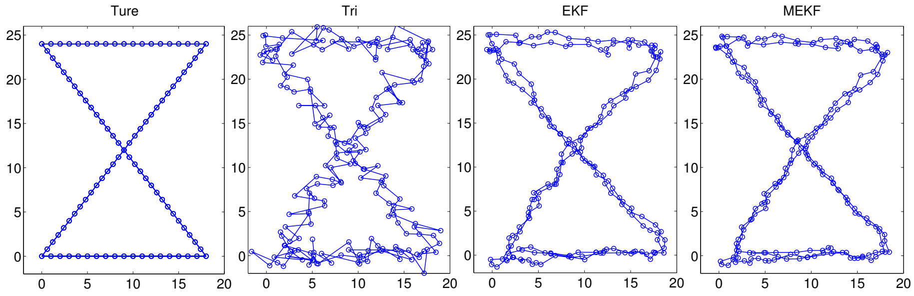


Figure 10: The localization results for user 4

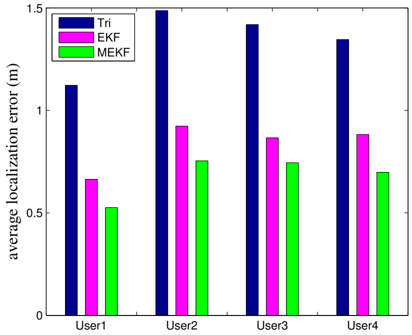


Figure 11: The average localization error for the users

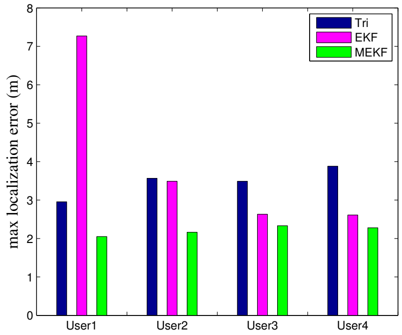


Figure 12: The maximum localization error for the users

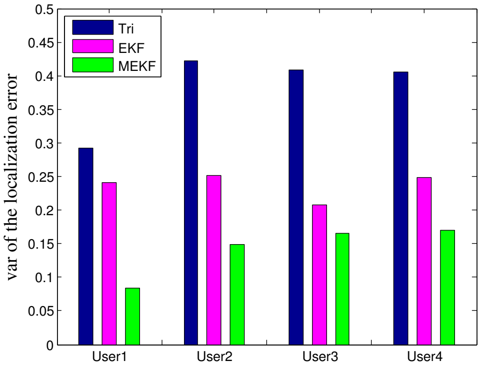


Figure 13: The variance of the localization error

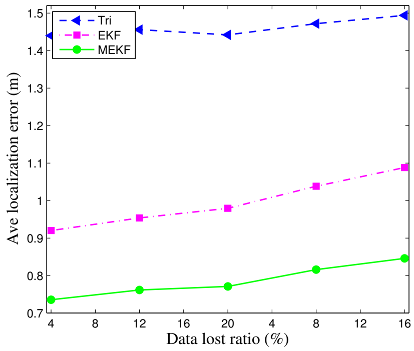


Figure 14: The average localization error vs. the data loss rate

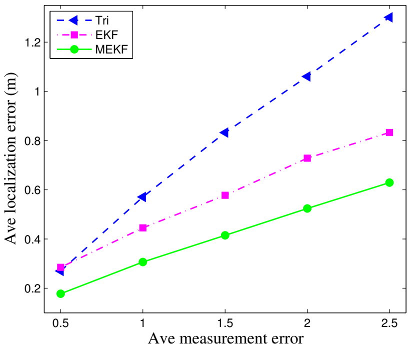


Figure 15: The average localization error vs. the measurement error of distance

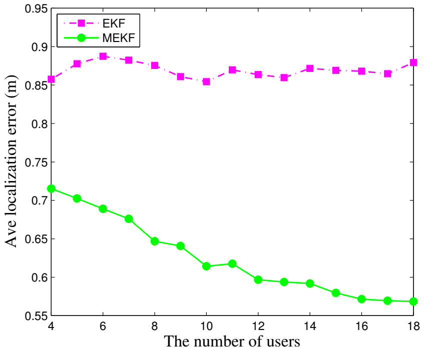


Figure 16: The average localization error vs. the number of users

71.8%, 38.0%, 12.8% and 12.8%, respectively. Moreover, from Fig. 13, the variance of the localization errors when using MEKF are below those of Tri by 71.4%, 64.9%, 58.1% and 46.0%, respectively, and below those of EKF by 65.3%, 40.9%, 31.4% and 30.3%, respectively. All of these results show that our proposed method with "mobile anchors" can achieve higher localization accuracy and more stable performance compared to Tri and EKF.

We also try to verify the localization performance of the three methods when the data loss rate changes by removing some data randomly. The average localization errors achieved by the three methods as the data loss rate increases from 4% to 20% are shown in Fig. 14. As expected, the average localization errors of all the methods generally increase as the data loss rate increases because less reference information can be obtained with the increment of the date loss rate. However, MEKF still outperforms Tri by 43.4% to 48.9% and outperforms EKF by 20.1% to 22.3%. These results further validate the effectiveness of our method with a high data loss rate.

Fig. 15 describes the average localization errors as the average distance measurement error increases from 0.5 m to 2.5 m. The localization errors achieved by the three methods generally trend upwards as the average measurement error increases, which is much more obvious for Tri. This is because that the accuracy of the reference information decreases with the increment of distance measurement error, and thus the localization accuracy decreases. However, MEKF still outperforms Tri by 34.2% to 51.6% and outperforms EKF by 24.5% to 37.7%, which validate that the proposed method can scale well with the distance measurement error.

The localization performance when the number of users in a group changes is presented in Fig. 16. The results demonstrate that the average localization error achieved by EKF is approximately the same, while that achieved by MEKF decreases when there are more users. This is because the increment of the users has no effect on the number of reference anchors for EKF. The average localization error achieved by MEKF is approximately 0.715 m when there are 4 non-localized users in a group, while it decreases to 0.572 m when the number increases to 16 and then tends to be stable with the increment of the user number. This is because more reference information can be got when there are more users, and thus the localization error can be reduced. When the number of users increases to a certain number, the localization error cannot be further reduced because the reference information available is sufficient to obtain the best performance, and the localization error may be caused by various other factors, such as data loss or measurement error.

What's more, to test the loclaization performance when the group members are located close to each other, we have done more experiments. Fig. 17 shows the localization results when the distance between the users increase. It can be seen from the results that all the methods can get better localization performance when the distance increase and it is because that the signal of the users may influence each other more serious when they are closer to each other.

From Fig. 18, we can see that the localization probability can be improved when the communication range of the users is increased. This is because a non-localized user can hear from more anchors (both fixed and mobile anchors) and obtain more reference information for localization. The localization probability achieved by MEKF increases from 73.4% to 100% when the communicate range increases from 15 m to 24 m, and the probability of Tri increases from 19.6% to 94.2%. MEKF outperforms Tri in all settings because of the increased reference information as a result of the introduction of the interoperable localization method.

5.2. *Real-world Experiment*

To further prove the validity of our proposed method, we conducted the real experiment on a 10×10 m^2 rectangular ground in the student canteen in Huaqiao University, as shown in Fig. 19. Seven localization nodes, as shown in Fig. 20, were used in our experiment. The main settings were about the same as the simulation experiment. We first tested the parameters of the nodes, such as the path attenuation index and then conducted the experiment. The results are as follows.

Fig. 21 presents the average localization errors achieved by the three algorithms. It can be seen that the localization errors achieved by the three methods are about the same as those achieved according to the simulation results, which demonstrates the localization performanc of the proposed scheme in practice environment.

Besides, we also calculate the percentage when the localization error less than 1 meter of the three methods,

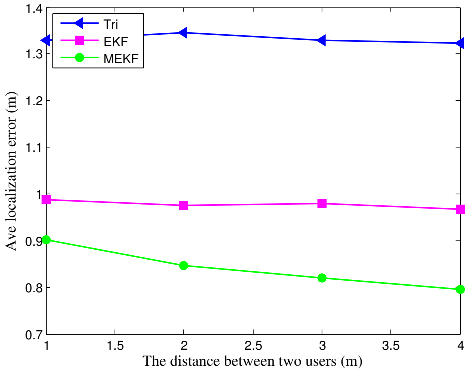


Figure 17: The average localization error vs. the distance between two users

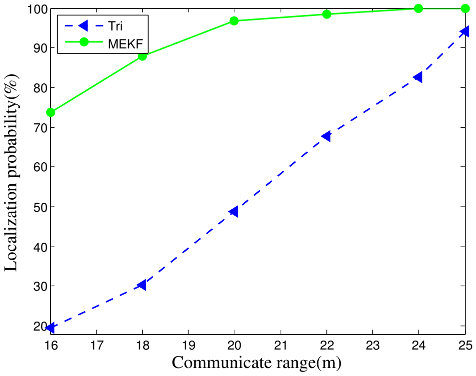


Figure 18: The localization probability vs. the communication range

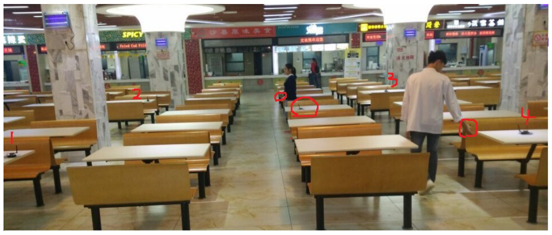


Figure 19: The real experimental scenario

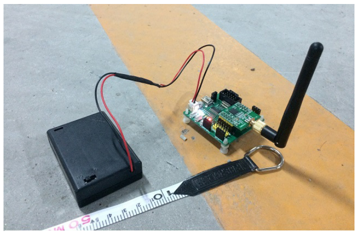


Figure 20: The localization nodes: cc2530

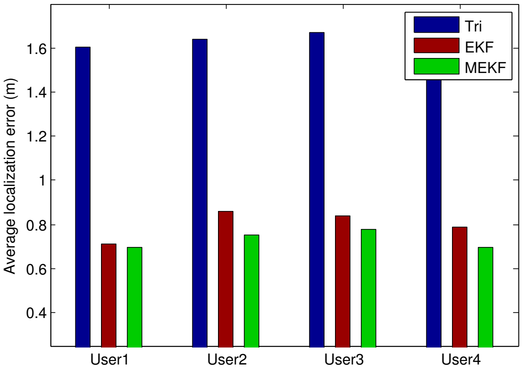


Figure 21: The average localization error of the users

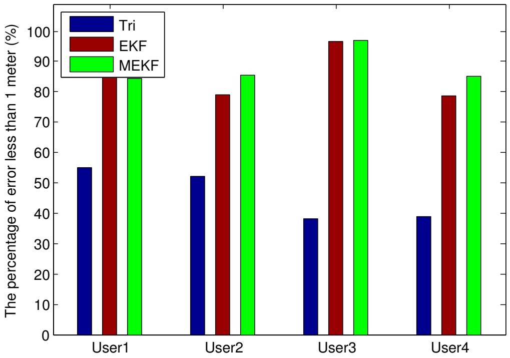


Figure 22: The percentage of localization error less than 1 meter

which is shown in Fig. 22. From the figure, we can know that MEKF achieves the largest ratio which is more than 80% of all the four users; the percentage achieved by EKF is a little small; and Tri achieves the smallest value which is about 50%. This result further proves the feasibility of our proposed method.

6. Conclusion

Focusing on the situation in which users may not be able to obtain enough information from anchors due to the effects of environmental noise and signal instability, which contribute to the poor performance of the traditional localization methods, we have designed the Interoperable Localization Method (ILM) for localizing mobile group users in this paper. First, we proposed localizing mobile users interoperably, in which the information exchanged among these users can be exploited to assist with localization. That is, localize mobile users using their interrelated information. Second, the reason why the proposed interoperable localization method can improve the localization probability and accuracy was given by theoretical analyses. Third, we extended the Kalman filter to alleviate the effects of environmental noise and signal instability. Finally, we validated the performance of the proposed localization scheme by extensive simulation experiments. The results showed that our approach significantly improved the localization accuracy and scaled quite well with the data loss rate, communication range of the users and distance measurement error.

Appendix

Theorem 6. *If one of the users can receive the signals of all three anchors and other users cannot receive the signals of any anchors (case 1 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 can hear all three anchors while U_2 and U_3 cannot hear any anchors. U_1 can be localized because it can hear three non-collinear anchors. For U_2 and U_3, because they can only hear U_1, whose location is known, they are respectively distributed around two concentric circles that share the same center (A_1) and have different radiuses (d_{12} and d_{13}). If one possible group of U_2 and U_3 can satisfy the distance condition of d_{23}, then locations that are obtained by rotating around the center can also satisfy the condition. Therefore, the users cannot be localized in this situation. □

Theorem 7. *If one of the users can receive the signals of two anchors, the second user can receive the signal of the third anchor, and the third user cannot receive the signals of any anchors (case 2 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 can hear A_1 and A_2, U_2 can hear A_3, and U_3 cannot hear any anchors. Then,

1. If $d_{A_1A_2} = d_1 + d_1'$, i.e., U_1 is on line A_1A_2, then U_1 can be positioned. For U_2, because it can hear U_1 and A_3, consider the following two cases. (a) If $d_{12} = d_{U_1A_3} - d_2$, i.e., U_2 is on line U_1A_3, then it can be localized. In this case, U_3 cannot be localized as it can only hear U_1 and U_2. (b) If $d_{12} < d_{U_1A_3} - d_2$, i.e., U_2 is not on line U_1A_3, then two possible locations of U_2 can be obtained. For every possible U_2, two possible positions of U_3 can be obtained, which are symmetric with respect to line U_1U_2. Thus four groups of possible localizations can be obtained in this condition. Therefore, the users cannot be located in this situation.
2. If $d_{A_1A_2} < d_1 + d_1'$, i.e., U_1 is not on line A_1A_2, then two possible localizations (U_1 and U_1') can be obtained, which are symmetric with respect to line A_1A_2. For U_2, (a) If it is on line U_1A_3, the intersections of circle A_3 (with center A_3 and radius d_3) and lines U_1A_3 and $U_1'A_3$, which are denoted as U_2 and U_2', respectively, are the possible positions of U_2. A_1, A_2 and A_3 are non-collinear anchors, and thus $U_1U_2 \neq U_1'U_2'$, i.e., only one group of the possible positions can meet the conditions. This can be seen in Fig. 23(a). Thus, U_1 and U_2 can be localized. U_3 cannot be positioned as it can only hear U_1 and U_2. Namely, the users cannot be positioned in this situation. (b) If U_2 is not on line U_1A_3, then four possible locations of U_2 can be obtained, which are symmetric with respect to line U_1A_3 and $U_1'A_3$, which is shown in Fig. 23(b). For U_3, because it can hear U_1 and U_2, it can also obtain two possible positions for different groups of U_1 and U_2. Therefore, the users cannot be localized in this situation.

□

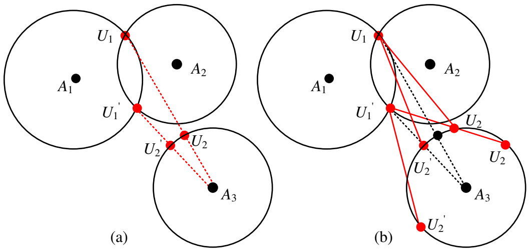


Figure 23: The localization results of U_2 when U_1 is not on line A_1A_2 ((a) represents the situation when U_2 is on line U_1A_3, and (b) describes the situation where U_2 is not on line U_1A_3)

Theorem 8. *If one of the users can receive the signals of two anchors and the other two users can receive the signal of the third anchor (case 3 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 can hear A_1 and A_2 and that U_2 and U_3 can hear A_3, then,

1. If $d_{A_1A_2} = d_1 + d_1'$, i.e., U_1 is on line A_1A_2, then U_1 can be localized. U_2 and U_3 can hear U_1 and A_3; then, (a) If they are on line U_1A_3, then they can be localized. (b) If only one of them (suppose U_2) is on line U_1A_3, then U_2 can be positioned. Two possible locations of U_3 that are symmetric with respect to line U_1A_3 can be obtained because it can hear U_1, U_2 and A_3, who are in line. Therefore, the users cannot be localized. (c) If none are not on line U_1A_3, two possible positions, for U_2 that are symmetric with respect to line U_1A_3 can be obtained. For certain U_2, U_3 can be positioned because it can hear the three non-collinear nodes U_1, U_2 and A_3. Therefore, the users cannot be localized in this situation.
2. If $d_{A_1A_2} < d_1 + d_1'$, i.e., U_1 is not on line A_1A_2, then two possible localizations of U_1 (U_1 and U_1') , that are symmetric with respect to line A_1A_2 can be obtained. For certain U_1, as U_2 can hear U_1 and A_3, (a) If U_2 is on line U_1A_3, then U_2 can be positioned. Two possible locations of U_3 that are symmetric with respect to line U_1A_3 can be obtained because it can hear U_1, U_2 and A_3, who are in line. Therefore, the users cannot be localized. (b) If U_2 is not on line U_1A_3, two possible localizations that are symmetric with respect to line U_1A_3 can be confirmed. For certain U_1 and U_2, U_3 can be positioned because it can hear the three non-collinear nodes U_1, U_2 and A_3. In all, the users cannot be localized in this situation.

□

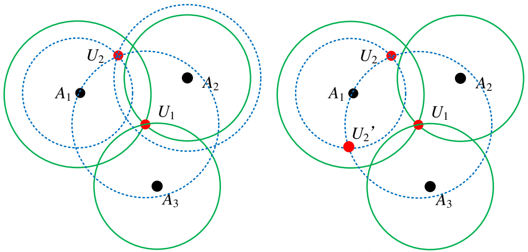
Theorem 9. *If two of the users can receive the signals of all three anchors and the last user cannot receive the signals of any anchors (case 4 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 and U_2 can hear all three anchors and that U_3 cannot hear any anchors. U_1 and U_2 can be positioned because they can hear three non-collinear anchors. For U_3, it can only hear U_1 and U_2: (a) If U_3 is on line U_1U_2, then it can be positioned. (b) If U_3 is not on line U_1U_2, then two possible localizations that are symmetric with respect to U_1U_2 can be obtained. Therefore, the users cannot be localized in this situation. □

Theorem 10. *If one of the users can receive the signals of all three anchors, the second can receive the signals of one or two of the anchors, and the third user cannot receive the signals of any anchors (case 5 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 can hear all three anchors, U_2 can hear one or two anchors, and U_3 cannot hear any anchors. Then:

1. If U_2 can hear two anchors, suppose that it can hear A_1 and A_2. U_1 can be positioned because it can hear three non-collinear anchors. U_2 can also be localized because it can hear A_1, A_2 and U_1, as shown in Fig. 24(a). For U_3, as it can hear U_1 and U_2, (a) If U_3 is on line U_1U_2, then it can be positioned. (b) If U_3 is not on line U_1U_2, then two possible localizations that are symmetric with respect to line U_1U_2 can be obtained. Thus, the users cannot be localized in this situation.
2. If U_2 can hear only one anchor, suppose that it can hear A_2 here. U_1 can be positioned because it can hear three non-collinear anchors. For U_2, because it can hear U_1 and A_2, (a) If it is on line U_1A_2, then it can be positioned. (b) If it is not on line U_1A_2, then two possible positions that are symmetric with respect to line U_1A_2 can be obtained, as shown in Fig. 24(b). Thus the users cannot be localized in this situation.



(a) (b)

Figure 24: The localization results of U_1 and U_2 ((a) represents the situation in which U_2 can hear A_1 and A_2, and (b) is the situation in which U_2 can only hear A_1)

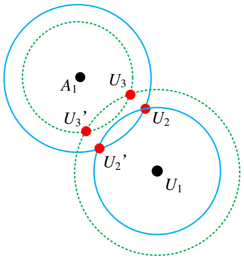


Figure 25: The localization results of U_2 and U_3 when they can hear the same anchor

□

Theorem 11. *If one of the users can receive the signals of all three anchors and the other two users can receive the signal of the same one anchor (case 6 in Table 1), then the users cannot be localized.*

Proof. Assume that U_1 can hear all three anchors and that U_2 and U_3 can hear A_1. U_1 can be positioned because it can hear three non-collinear anchors. For U_2, because it can hear U_1 and A_1, (a) If it is on line U_1A_1, then it can be localized. (b) If it is not on line U_1A_1, then two possible localizations that are symmetric with respect to line U_1A_1 can be obtained. For certain U_2, U_3 can be positioned because it can hear U_1, U_2 and A_1. Thus, two groups of possible localizations can be determined in this situation, as shown in Fig. 25. Therefore, the users cannot be localized in this situation. □

Theorem 12. *If each user can receive the signals of all three anchors (case 12 in Table 1), then the users can be localized.*

Proof. The users can be positioned as they can hear three non-collinear anchors in this situation. □

Acknowledgment

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